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Complete Set of Polarization Transfer Observables for the ^{12}C(p, n) Reaction at 296 MeV and 0°

Masanori DOZONO*, Tomotsugu WAKASA, Ema IHARA, Shun ASAJI, Kunihiro FUJITA[1], Kichiji HATANAKA[1], Takashi ISHIDA[2], Takaaki KANEDA[1], Hiroaki MATSUBARA[1], Yuji NAGASUE, Tetsuo NORO, Yasuhiro SAKEMI[3], Yohei SHIMIZU[1], Hidemitsu TAKEDA, Yuji TAMESHIGE[1], Atsushi TAMII[1] and Yukiko YAMADA

Department of Physics, Kyushu University, Fukuoka 812-8581
[1]*Research Center for Nuclear Physics, Osaka University, Osaka 567-0047*
[2]*Laboratory of Nuclear Science, Tohoku University, Sendai 982-0826*
[3]*Cyclotron and Radioisotope Center, Tohoku University, Sendai 980-8578*

A complete set of polarization transfer observables has been measured for the ^{12}C(p, n) reaction at $T_p = 296$ MeV and $\theta_{\rm lab} = 0°$. The total spin transfer $\Sigma(0°)$ and the observable f_1 deduced from the measured polarization transfer observables indicate that the spin–dipole resonance at $E_x \simeq 7$ MeV has greater 2^- strength than 1^- strength, which is consistent with recent experimental and theoretical studies. The results also indicate a predominance of the spin-flip and unnatural-parity transition strength in the continuum. The exchange tensor interaction at a large momentum transfer of $Q \simeq 3.6$ fm^{-1} is discussed.

KEYWORDS: complete set of polarization transfer observables, spin–dipole resonance, exchange tensor interaction

The charge exchange reaction at intermediate energies ($T \gtrsim 100$ MeV/A) is one of the best probes to study spin–isospin excitations in nuclei, such as spin–dipole (SD) excitations characterized by $\Delta L = 1$, $\Delta S = 1$, and $\Delta J^\pi = 0^-$, 1^-, and 2^-. In previous (p, n) and (n, p) experiments on ^{12}C,[1,2] spin–dipole resonances (SDRs) were found at $E_x \simeq 4$ and 7 MeV. Analysis of the angular distributions of the SDRs at $E_x \simeq 4$ and 7 MeV indicate that they consist of mainly 2^- and 1^- components, respectively. However, a recent ^{12}C$(\vec{d}, ^2$He$)^{12}$B experiment[3] suggested that the SDR at $E_x \simeq 7$ MeV in ^{12}B has more 2^- components than 1^- components. This suggestion is supported by a ^{12}C(^{12}C, ^{12}N)^{12}B experiment[4] and by theoretical calculations including tensor correlations.[5] Thus the spin-parity assignment of the SDR at $E_x \simeq 7$ MeV for the $A = 12$ system is still controversial.

A complete set of polarization transfer (PT) observables at 0° is a powerful tool for investigating the spin-parity J^π of an excited state. The total spin transfer $\Sigma(0°)$ deduced from such a set gives information on the transferred spin ΔS, which is independent of theoretical models.[6] Furthermore, information can be obtained on the parity from the observable f_1.[7] On the other hand, each PT observable is sensitive to the effective nucleon–nucleon (NN) interaction. The PT observables for $\Delta J^\pi = 1^+$ transitions have been used to study the exchange tensor interaction at large momentum transfers.[8,9]

In this Letter, we present measurements of a complete set of PT observables for the ^{12}C(p, n) reaction at $T_p = 296$ MeV and $\theta_{\rm lab} = 0°$. We have deduced the total spin transfer Σ and the observable f_1 using the measured PT observables in order to investigate the spin-parity structure in both the SDR and continuum regions. We also compare the PT observables for the ^{12}C$(p, n)^{12}$N(g.s.; 1^+) reaction with distorted-wave impulse approximation (DWIA) calculations employing the effective NN interaction in order to assess the effective tensor interaction at a large exchange momentum transfer of $Q \simeq 3.6$ fm^{-1}.

Measurements were carried out at the neutron time-of-flight facility[10] at the Research Center for Nuclear Physics (RCNP), Osaka University. The proton beam energy was 296 MeV and the typical current and polarization were 500 nA and 0.70, respectively. The neutron energy and polarization were measured by the neutron detector/polarimeter NPOL3.[11] We used a natural carbon (98.9% ^{12}C) target with a thickness of 89 mg/cm^2. The measured cross sections were normalized to the 0° ^{7}Li$(p, n)^7$Be(g.s. + 0.43 MeV) reaction, which has a center of mass (c.m.) cross section of $\sigma_{\rm c.m.}(0°) = 27.0 \pm 0.8$ mb/sr at this incident energy.[12] The systematic uncertainties of the data were estimated to be 4–6%.

Asymmetries of the ^{1}H$(\vec{n}, p)n$ and ^{12}C$(\vec{n}, p)$X reactions in NPOL3 were used to deduce the neutron polarization. The effective analyzing power $A_{y;\rm eff}$ of NPOL3 was calibrated by using polarized neutrons from the ^{12}C$(\vec{p}, \vec{n})^{12}$N(g.s.;1^+) reaction at 296 MeV and 0°. A detailed description of the calibration can be found in Ref. 11. The resulting $A_{y;\rm eff}$ was $0.151 \pm 0.007 \pm 0.004$, where the first and second uncertainties are statistical and systematic, respectively.

Figure 1 shows the double differential cross section and a complete set of PT observables D_{ii} ($i = S$, N, and L) at 0° as a function of excitation energy E_x. The laboratory coordinates at 0° are defined so that the normal ($\hat{\boldsymbol{N}}$) direction is the same as $\hat{\boldsymbol{N}}$ at finite angles (normal to the reaction plane), the longitudinal ($\hat{\boldsymbol{L}}$) direction is along the momentum transfer, and the sideways ($\hat{\boldsymbol{S}}$) direction is given by $\hat{\boldsymbol{S}} = \hat{\boldsymbol{N}} \times \hat{\boldsymbol{L}}$. The data of the cross section in Fig. 1 have been sorted into 0.25-MeV

*E-mail address: dozono@kutl.kyushu-u.ac.jp

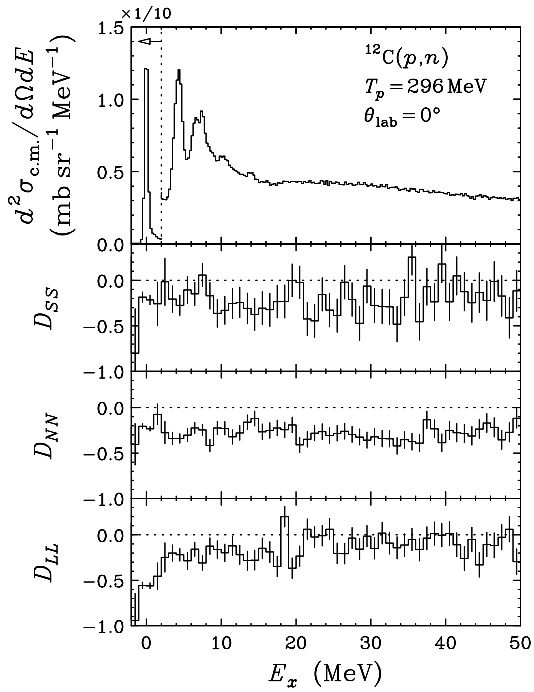

Fig. 1. Double differential cross section (top panel) and a complete set of polarization transfer observables (bottom three panels) for the ^{12}C(p,n) reaction at $T_p = 296$ MeV and $\theta_{\rm lab} = 0°$. The error bars represent statistical uncertainties only.

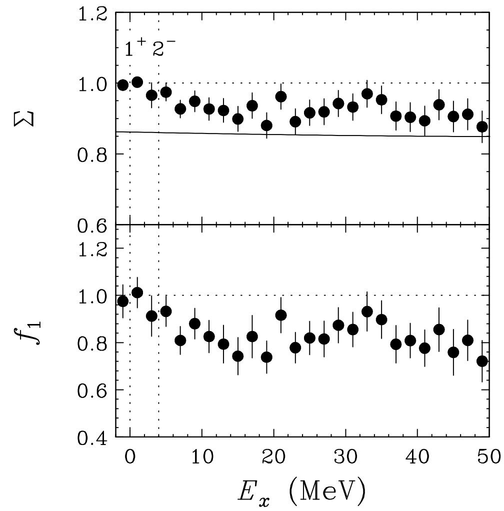

Fig. 2. Total spin transfer Σ (top panel) and observable f_1 (bottom panel) for the ^{12}C(p,n) reaction at $T_p = 296$ MeV and $\theta_{\rm lab} = 0°$. The error bars represent statistical uncertainties only. The solid line shows the values of Σ for free NN scattering.

bins, while the data of $D_{ii}(0°)$ have been sorted into 1-MeV bins to reduce statistical fluctuations. A high energy resolution of 500 keV full width at half maximum (FWHM) was realized by NPOL3, which enabled us to observe clearly two SDR peaks at $E_x \simeq 4$ and 7 MeV. It should be noted that the $D_{NN}(0°)$ value should be equal to the corresponding $D_{SS}(0°)$ value because the $\hat{\boldsymbol{N}}$ direction is identical to the $\hat{\boldsymbol{S}}$ direction at 0°. The experimental $D_{NN}(0°)$ and $D_{SS}(0°)$ values are consistent with each other within statistical uncertainties over the entire range of E_x, demonstrating the reliability of our measurements.

Figure 2 shows the total spin transfer $\Sigma(0°)$ and the observable f_1 defined as[6,7]

$$\begin{aligned}\Sigma(0°) &= \frac{3-[2D_{NN}(0°)+D_{LL}(0°)]}{4},\\ f_1 &= \frac{1-2D_{NN}(0°)+D_{LL}(0°)}{2[1+D_{LL}(0°)]},\end{aligned} \tag{1}$$

as a function of excitation energy E_x. The $\Sigma(0°)$ value is either 0 or 1 depending on whether $\Delta S = 0$ or $\Delta S = 1$, which is independent of theoretical models.[6] The f_1 value is either 0 or 1 depending on the natural-parity or unnatural-parity transition if a single ΔJ^π transition is dominant.[7] The $\Sigma(0°)$ and f_1 values of the spin-flip unnatural-parity 1^+ and 2^- states at $E_x = 0$ and 4 MeV, respectively, are almost unity, which is consistent with theoretical predictions. The continuum $\Sigma(0°)$ values are almost independent of E_x and take values larger than 0.88 up to $E_x = 50$ MeV, indicating the predominance of the spin-flip strength. The solid line in the top panel of Fig. 2 represents the free NN values of $\Sigma(0°)$ for the corresponding kinematical condition.[13] Enhancement of $\Sigma(0°)$ relative to the free NN values means enhancement of the $\Delta S = 1$ response relative to the $\Delta S = 0$ response in nuclei at small momentum transfers, which is consistent with previous studies of (p,p') scattering.[14,15] The large values of $f_1 \geq 0.72$ up to $E_x = 50$ MeV indicate a predominance of the unnatural-parity transition strength in the continuum, consistent with the ^{90}Zr(p,n) result at 295 MeV.[7]

The top panel of Fig. 3 shows the spin-flip $(\sigma\Sigma)$ and non-spin-flip $(\sigma(1-\Sigma))$ cross sections as filled and open circles, respectively, as functions of E_x. The bottom panel shows the unnatural-parity dominant (σf_1) and natural-parity dominant $(\sigma(1-f_1))$ components of the cross section as filled and open circles, respectively. The solid lines are the results of peak fitting of the spectra with Gaussian peaks and a continuum. The continuum was assumed to be the quasi-free scattering contribution, and its shape was given by the formula given in Ref. 16. It should be noted that the spin-flip unnatural-parity 1^+ and 2^- states at $E_x = 0$ and 4 MeV, respectively, form peaks only in the $\sigma\Sigma$ and σf_1 spectra. It is found that the prominent peak at $E_x \simeq 7$ MeV is the spin-flip unnatural-parity component with a J^π value estimated to be 2^- because the $D_{ii}(0°)$ values are consistent with the theoretical prediction for $J^\pi = 2^-$.[17] In the $\sigma(1-f_1)$ spectrum, possible evidence for SD 1^- peaks is seen at $E_x \simeq 7$, 10, and 14 MeV. The top and bottom panels of Fig. 4 show theoretical calculations for the unnatural-parity and natural-parity SD strengths, respectively.[5] Experimentally extracted peaks in the σf_1 and $\sigma(1-f_1)$ spectra are also shown. Concentration of the SD 2^- strength at three peaks at $E_x \simeq 4$, 8, and 13 MeV has been predicted. Our data agree with this prediction qualitatively, but give slightly different excitation energies of $E_x \simeq 4$, 7, and 11 MeV. On the other hand, the SD 1^- strength has been predicted to be quenched and fragmented due to tensor correlations.[5] The experimental re-

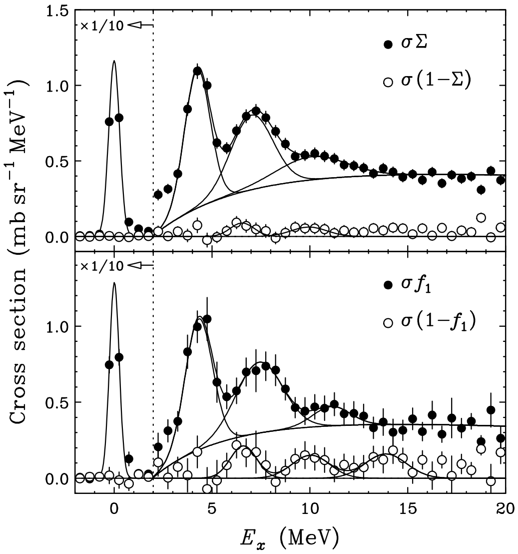

Fig. 3. Cross sections separated by Σ (top panel) and f_1 (bottom panel) for the ^{12}C(p,n) reaction at $T_p = 296$ MeV and $\theta_{\rm lab} = 0°$. The solid lines show peak fitting of the spectra with Gaussian peaks and a continuum.

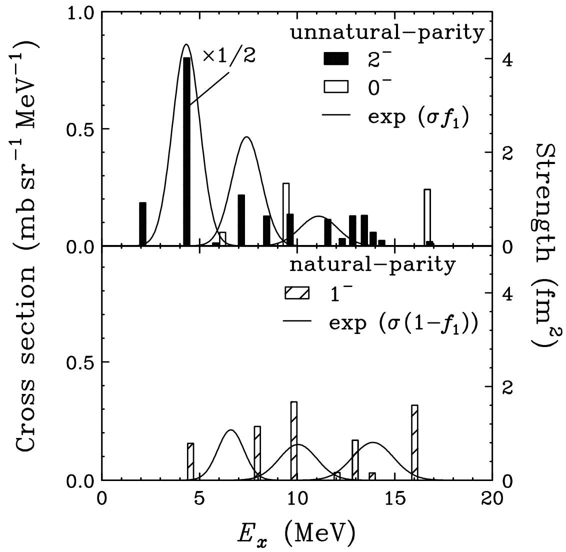

Fig. 4. SD strengths for unnatural-parity (top panel) and natural-parity (bottom panel) taken from Ref. 5. The solid lines represent peaks obtained by fitting σf_1 (top panel) and $\sigma(1-f_1)$ (bottom panel) spectra.

sults are spread over a wide region of $E_x \simeq$ 5–16 MeV and exhibit similar cross sections, which supports fragmentation of the SD 1^- strength.

Effective tensor interactions at $q \simeq$ 1–3 fm^{-1} have mainly been studied using high spin stretched states.[18,19] The present $D_{ii}(0°)$ data can give information on the exchange tensor interaction at an extremely large exchange momentum transfer of $Q \simeq 3.6$ fm^{-1}. In the Kerman–McNanus–Thaler (KMT) representation,[20] the NN scattering amplitude is represented as

$$\begin{aligned} M(q) = A &+ \tfrac{1}{3}(B+E+F)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + C(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\hat{\boldsymbol{n}} \\ &+ \tfrac{1}{3}(E-B)S_{12}(\hat{\boldsymbol{q}}) + \tfrac{1}{3}(F-B)S_{12}(\hat{\boldsymbol{Q}}), \end{aligned} \tag{2}$$

where S_{12} is the tensor operator, $\hat{\boldsymbol{q}}$ and $\hat{\boldsymbol{Q}}$ are direct and exchange momentum transfers, respectively, and $\hat{\boldsymbol{n}} = \hat{\boldsymbol{Q}} \times \hat{\boldsymbol{q}}$. In a plane-wave impulse approximation (PWIA), the PT observables for the Gamow–Teller (GT) transition at 0° are simply expressed using parameters A–F as[17]

$$\begin{aligned} D_{NN}(0°) = \quad D_{SS}(0°) \quad &= \frac{-F^2}{2B^2+F^2}, \\ D_{LL}(0°) \ &= \frac{-2B^2+F^2}{2B^2+F^2}. \end{aligned} \tag{3}$$

If there is no exchange tensor $S_{12}(\hat{\boldsymbol{Q}})$ interaction (i.e., $F = B$), then $D_{ii}(0°) = -1/3$.

The measured PT observables $D_{ii}(0°)$ for the GT ^{12}C$(\vec{p},\vec{n})^{12}$N(g.s.;1^+) transition are listed in Table I, where the listed uncertainties are statistical only. The present $D_{NN}(0°)$ and $D_{SS}(0°)$ values are consistent with each other, as expected, and the present $D_{NN}(0°)$ value agrees with the previously measured $D_{NN}(0°)$ value at the same energy.[9] The experimental values deviated from $-1/3$, which indicates that there are contributions from both the exchange tensor interaction at $Q \simeq 3.6$ fm^{-1} and nuclear distortion effects.

In order to assess these effects quantitatively, we performed microscopic DWIA calculations using the computer code DW81.[21] The transition amplitudes were calculated from the Cohen–Kurath wave functions[22] assuming Woods–Saxon radial dependence.[23] Distorted waves were generated using the optical model potential (OMP) for proton elastic scattering data on ^{12}C at 318 MeV.[24] We used the effective NN interaction parameterized by Franey and Love (FL) at 270 or 325 MeV.[25]

First, we examined the sensitivity of the DWIA results to the OMPs by using two different parameters.[24,26] The OMP dependence of $D_{ii}(0°)$ was found to be less than 0.01. This insensitivity allows us to use $D_{ii}(0°)$ as a probe to study the effective NN interaction. Table I shows the DWIA results for $D_{ii}(0°)$ with the NN interaction at 270 and 325 MeV. It is found that the $D_{ii}(0°)$ values, and $D_{LL}(0°)$ in particular, are sensitive to the choice of the NN interaction. These differences are mainly due to the exchange tensor interaction $S_{12}(Q)$ at $Q \simeq 3.6$ fm^{-1}. The real part of $S_{12}(Q)$ for the FL 325 MeV interaction is about twice as large as that for the FL 270 MeV interaction at $Q \simeq 3.6$ fm^{-1} (see Fig. 3 of Ref. 9). The experimental $D_{ii}(0°)$ values support the DWIA results with the FL 270 MeV interaction, which indicates that the exchange tensor part of the FL 270 MeV interaction has an appropriate strength at $Q \simeq 3.6$ fm^{-1}. This conclusion has already been reported for $D_{NN}(0°)$ data,[9] however, the present data make the conclusion more rigorous because of the high sensitivity of $D_{LL}(0°)$ to the exchange tensor interaction.

In summary, a complete set of PT observables for the ^{12}C(p,n) reaction at $T_p = 296$ MeV and $\theta_{\rm lab} = 0°$ has been measured. The total spin transfer $\Sigma(0°)$ and the observable f_1 are deduced in order to study the spin-parity structure in both the SDR and continuum regions. The $\Sigma(0°)$ and f_1 values show that the SDR at

		$D_{NN}(0°)$	$D_{SS}(0°)$	$D_{LL}(0°)$
Exp.	This work	-0.216 ± 0.019	-0.210 ± 0.039	-0.554 ± 0.023
	ref. 9	-0.215 ± 0.019	–	–
DWIA	FL 270 MeV	-0.225	-0.225	-0.550
	FL 325 MeV	-0.191	-0.191	-0.619

Table I. PT observables $D_{ii}(0°)$ for the GT ^{12}C$(\vec{p},\vec{n})^{12}$N(g.s.;1$^+$) transition at 296 MeV and 0° compared with theoretical calculations.

$E_x \simeq 7$ MeV has greater 2^- strength than 1^- strength, which agrees with the recent theoretical prediction. In the continuum up to $E_x \simeq 50$ MeV, a predominance of the spin-flip and unnatural-parity transition strength is also found. We have compared the PT observables of the ^{12}C$(p,n)^{12}$N(g.s.;1$^+$) reaction with DWIA calculations employing the FL interaction. The exchange tensor interaction of the FL 270 MeV interaction is found to be more appropriate at $Q \simeq 3.6$ fm^{-1} than that of the FL 325 MeV interaction. Thus a complete set of PT observables provides rigorous information not only on the spin-parity structure in nuclei but also on the effective NN interaction.

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